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STRUCTURAL EVALUATION OF CONCRETE SLABS USING FALLING WEIGHT DEFLECTOMETER RESULTS

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This report describes procedures for evaluating the results from non-destructive tests (NDT) to determine the properties of a concrete slab so that its load carrying capacity can be evaluated. The procedure is based on measuring the response of a slab to impulse type load (Falling Weight) and back calculating slab support conditions and slab stiffness. Slab stiffness is a combination of the modulus of the slab material and slab thickness. If one of these two properties is known or can be estimated, the other can be calculated directly. The procedure, based on medium thick plate theory, is mathematically rigorous and relies on closed form solution to elastic plate theory. Support conditions can be expressed in terms of either a Winkler type foundation (dense liquid) or as an elastic solid. An example use for this procedure is to check the effective thickness of newly constructed slabs without the necessity of coring the slabs.

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INTRODUCTION

In-situ properties of Portland Cement Concrete (PCC) and foundation support characteristics are required to evaluate the structural capacity of concrete slabs. An easy to use and efficient interpretation scheme using Falling Weight Deflectometer (FWD) data was developed in this study. A closed form, backcalculation procedure based on a consistent and theoretically rigorous approach utilizing the principles of dimensional analysis, applicable to two-layer, rigid pavement systems is presented. The backcalculation process also utilizes the "area" concept for defining the deflection basin, first proposed by Hoffman and Thompson (1). The approach presented herein simplifies considerably the effort required in interpreting nondestructive testing (NDT) data. A unique feature of this approach is that in addition to yielding the required backcalculated parameters, it also allows an evaluation of the degree to which the in-situ system behaves as idealized by theory. The theories used in the development of the procedure assume that the pavement consists of a medium-thick, elastic plate, supported by a dense liquid (DL) or an elastic solid (ES) subgrade. The procedure provides the means to determine the support moduli in terms of either the dense liquid modulus of subgrade reaction, "k" value, or the elastic modulus, E. Using the charactieristics of these two support media, the measured

response of the slab can be compared to that predicted by theory for both types of support and to thus determine which characterization best represents the true support conditions.

If the elastic modulus of the concrete is known or can be determined, then the slab thickness can be determined using the procedure. Thus, the procedure can be used as a tool for construction quality assurance by determining the effective slab thickness without the necessity of coring.

FUNDAMENTAL CONCEPTS

The backcalculation scheme used in this study employs two fundamental and theoretically valid concepts. These are:

1. A unique relationship exists between the deflection basin area, AREA, and the radius of relative stiffness, ℓ, of the pavement-subgrade system (2); and
2. Deflections in rigid pavements, expressed in a dimensionless form, are solely a function of the governing load size ratio, (a/ℓ), where a is the radius of the applied load (3).

All three of these quantities (AREA, ℓ, and a) are expressed in inches. The area of the deflection basin is calculated as follows:

$$\text{AREA [in.]} = 6 \left[1 + 2 (D_1/D_0) + 2 (D_2/D_0) + (D_3/D_0) \right] \quad (1)$$

where D_0, D_1, D_2 and D_3 are the FWD deflections recorded at 0, 12 24 and 36 in. from the center of the loading plate, respectively.

Now, the radius of relative stiffness of the pavement-subgrade system is defined by:

For the DL foundation: $\ell = \ell_k = \sqrt[4]{[Eh^3/\{12(1-\mu^2)k\}]}$ (2a)

For the ES foundation: $\ell = \ell_e = \sqrt[3]{[Eh^3(1-\mu_s^2)/\{6(1-\mu^2)E_s\}]}$ (2b)

where:

- E: slab Young's modulus;
- E_s: soil Young's modulus;
- h: slab thickness;
- μ: slab Poisson ratio;
- μ_s: soil Poisson ratio; and
- k: modulus of subgrade reaction.

Application of dimensional analysis indicates that a unique relationship between AREA and ℓ exists and is valid for any chosen plate size and sensor arrangement. Figure 1 shows the AREA vs. ℓ curves, for four different loading and support conditions, assuming four sensors at 12-in. spacing are employed.

Inspection of the interior loading formula presented by Westergaard (4), shows that the maximum deflection in a two-layer, rigid pavement system may be rewritten in the following nondimensional form:

$$d_0 = D_0 \, D \, / \, (P \, \ell^2) = D_0 \, k \, \ell^2 \, / \, P \quad (3)$$

where P is the applied load, and D is the slab flexural stiffness, which is given by:

$$D = E \, h^3 \, / \, \{12 \, (1-\mu^2)\} \quad (4)$$

Similar expressions can be derived for the other three FWD deflections, i.e.:

$$d_i = D_i\ D\ /\ (P\ \ell^2) = D_i\ k\ \ell^2\ /\ P \qquad (i=0,3) \qquad (5)$$

where d_i denotes the four nondimensional sensor deflections corresponding to the measured deflections, D_i. The nondimensional deflections are known functions of the ratio (a/ℓ) only. In the case of a constant plate load radius they are uniquely defined by ℓ, alone. Figure 2 shows the variation with ℓ of dimensionless deflections, d_i, for a circular load, radius a = 5.9055 in. (= 300 mm). The curves corresponding to d_0 are defined by the interior loading maximum deflection formulae presented in References 4 and 5, for the DL, and in Reference 6 for the ES foundations. The remainder of the curves in Fig. 2 were derived more recently and are presented in References 2 and 7.

OUTLINE OF THE BACKCALCULATION PROCEDURE

On the basis of the two fundamental concepts discussed above, the backcalculation procedure is as follows:

(1) Determine the applied FWD applied load, P, and the resulting deflections, D_0, D_1, D_2 and D_3.

(2) Calculate the area of the deflection basin, AREA.

(3) Enter Fig. 1 with this AREA-value, and pick up the corresponding radius of relative stiffness value, ℓ.

(4) Enter Fig. 2 with this ℓ-value, and determine the corresponding dimensionless deflections, d_i.

(5) Backcalculate the subgrade support values, as follows:

For the DL foundation: $k = (d_i/D_i)\ (P/\ell^2)$ (6a)

For the ES foundation: $C = E_s\ /\ (1-\mu_s^2) = (d_i/D_i)\ (2P/\ell)$ (6b)

For a chosen value of the subgrade Poisson's ratio, (say, μ_s = 0.4 to 0.5), Eq. (6b) can be rewritten to yield the foundation modulus, E_s:

$$E_s = (1-\mu_s^2)\ (d_i/D_i)\ (2P/\ell) \tag{7}$$

(5) Backcalculate the slab flexural stiffness, as follows:

$$D = E\ h^3 \ /\ \{12\ (1-\mu^2)\} = (d_i/D_i)\ P\ \ell^2 \tag{8}$$

Thus, if the slab thickness, h, is known, the slab modulus can be calculated using:

$$E = \{12(1-\mu^2)/h^3\}\ (d_i/D_i)\ P\ell^2 \tag{9}$$

Alternatively, if the slab modulus, E, is known, one can backcalculate thickness, h, from:

$$h = \sqrt[3]{\left[\ \{12(1-\mu^2)/E\}\ (d_i/D_i)\ P\ell^2\ \right]} \tag{10}$$

For the slab Poisson ratio, μ, a value of 0.15 may be used.

Note that using these backcalculation equations (Eq. 6 through 10), four determinations of each pavement system parameter (k, E_s, h or E) are possible, each corresponding to one measured deflection, D_i. This provides a control on the accuracy of individual sensor readings, as well as a measure of <u>in-situ</u> material variability, and of the departure of the real system from the idealized conditions assumed when developing the theory.

APPLICATION OF CLOSED-FORM BACKCALCULATION PROCEDURE

To illustrate the application of the procedure described above, a set of FWD data, collected from a PCC pavement section along Interstate 80 in Illinois, will be used to backcalculate the pavement parameters. The radius of the load plate was the standard a = 5.9055 in. = 300 mm, and the recorded load, P, was

7792 lbs. Sensors were located at 0, 12, 24 and 36 in. from the center of the plate. Recorded deflections, in inches, were as follows:

$D_0 = 0.0030$; $D_1 = 0.0028$; $D_2 = 0.0024$; $D_3 = 0.0021$.

Substituting these deflections in Eq. (1) yields:

AREA = 6 [1 + 2 (2.8/3.0) + 2 (2.4/3.0) + (2.1/3.0)] = 31.00 in.

From Fig. 1, the corresponding radius of relative stiffness values are: DL: $\ell_k = 39$ in.; ES: $\ell_e = 28$ in.

Entering Fig. 2 with these ℓ-values, one obtains the following nondimensional deflections:

DL Foundation: $d_0 = 0.124$; $d_1 = 0.116$; $d_2 = 0.102$; $d_3 = 0.084$.

ES Foundation: $d_0 = 0.190$; $d_1 = 0.176$; $d_2 = 0.154$; $d_3 = 0.130$.

Thus, Equations (6a) and (6b) give the following backcalculated subgrade support values (assuming $\mu_s = 0.45$ for the ES):

For the DL Foundation:

$k = (0.124/0.0030)\ (7792 / 39^2) = 212$ pci based on D_0;

$k = (0.116/0.0028)\ (7792 / 39^2) = 212$ pci based on D_1;

$k = 218$ pci based on D_2; and $k = 205$ pci based on D_3.

The mean of these backcalculated k-values is 212 pci and their coefficient of variation (COV) is 2.15%.

For the ES Foundation:

$E_s = (1-0.45^2)\ (0.190/0.0030)\ (2x7792/28) = 28,111$ psi based on D_0;

$E_s = (1-0.45^2)\ (0.176/0.0028)\ (2x7792/28) = 27,900$ psi based on D_1;

E_S = 28,481 psi based on D_2; and E_S = 27,477 psi based on D_3.

Thus, the average backcalculated value of the elastic solid foundation modulus is 27,992 psi, with a COV of 1.30%.

Assuming μ = 0.15 and E = 4,500,000 psi, Eq. (10) is used to backcalculate the slab thickness, h. For the DL Foundation:

$$h = \sqrt[3]{\left\{ (12(1-0.15^2)/4,500,000)\ (0.124/0.0030)\ 7792\ (39)^2 \right\}}$$

$$= 10.85 \text{ in. based on } D_0.$$

Similarly, h = 10.86 in. based on D_1; h = 10.95 in. based on D_2; and h = 10.73 in. based on D_3. In this case, the mean slab thickness is found to be 10.85 in., and the corresponding COV 0.72%.

For the ES Foundation:

$$h = \sqrt[3]{\left\{ (12(1-0.15^2)/4,500,000)\ (0.190/0.0030)\ 7792\ (28)^2 \right\}}$$

$$= 10.03 \text{ in. based on } D_0.$$

By comparison, h = 10.00 in. based on D_1; h = 10.07 in. based on D_2; and h = 9.95 in. based on D_3. The backcalculated values of h for the elastic solid foundation have a mean of 10.01 in., and a COV of 0.44%.

Alternatively, if the thickness is known to be 10.0 inches, Eq. (9) is used with μ = 0.15 to backcalculate the slab modulus. Thus, for the DL Foundation:

$$E = (12(1-0.15^2)/10.0^3)\ (0.124/0.0030)\ 7792\ (39)^2$$

$$= 5,746,145 \text{ psi based on } D_0.$$

The other backcalculated E-values are: E = 5,759,385 psi based on D_1; E = 5,908,335 psi based on D_2; and E = 5,560,786 psi based on

D_3. Hence, an average value of E = 5,743,662 psi is determined (COV = 2.15%, identical to that for k-value).

For the ES Foundation:

$$E = \{12(1-0.15^2)/10.0^3\}\ (0.190/0.0030)\ 7792\ (28)^2$$

$$= 4{,}538{,}323 \text{ psi based on } D_0.$$

The corresponding values for the other deflections are E = 4,504,200 psi based on D_1; E = 4,598,037 psi based on D_2; and E = 4,435,954 psi based on D_3. The mean slab modulus is 4,519,128 psi and the COV is 1.30% (which is identical to that for E_s).

The results of the brief statistical analysis of the parameters backcalculated above provide some useful insights pertaining to the testing procedure adopted, and the observed behavior of the in-situ pavement system. In all cases, a coefficient of variation substantially smaller than 10%, say, was obtained, indicating that no major blunders were involved in the individual sensor readings. If one of the sensors had malfunctioned, the backcalculated parameters based on that particular deflection reading would have been significantly different from the remainder, thus alerting the engineer to the probability of an error. In addition, Fig. 2 indicates that d_0 and d_1 are relatively insensitive to changes in the value of ℓ, compared to d_2 and d_3. Thus, it may be concluded that the latter are more reliable backcalculation tools. On the other hand, the actual measured deflections D_0 and D_1 are probably more accurate than D_2 and D_3, owing to their larger magnitude and the equal sensitivity of all sensors, as used in conventional practice.

Therefore, it may be desirable to use sensors of increased sensitivity for measuring deflections further away from the center of the applied load. Furthermore, care should be exercised in the field to achieve good seating of the loading plate, as well as of the sensors.

ADVANTAGES OF CLOSED-FORM BACKCALCULATION PROCEDURE USED

The major strengths of the method used in this study, compared to other currently available backcalculation schemes are as follows:

(a) It is founded upon a rigorous, sound and fundamental theoretical basis, and is extremely powerful and versatile.

(b) When the backcalculation is performed on a personal computer (computer program ILLI-BACK), execution time per deflection basin is trivial (≈1 sec.). This permits the interpretation of a vast amount of NDT in a very reasonable time. In contrast, a typical back-calculation for a two-layer slab-on-grade system using BISDEF (8) takes about 600 CPU sec. to complete (9).

(c) Each sensor reading provides an independent estimate of the backcalculated parameters. This allows the engineer to investigate the sources of variability in field measurements and materials. Either of the two major subgrade models, namely the dense liquid or the elastic solid foundation, may be employed, providing a rare opportunity for meaningful comparisons between the two. The departure of in-situ behavior from the theoretical assumptions is reflected in the backcalculation statistics obtained. This affords an estimate of the relative location of the actual pavement system behavior within the spectrum defined by the two extreme soil idealizations.

(d) There is no need for the provision of seed moduli in this approach. These moduli greatly affect the accuracy of other back-calculation schemes (10). If the slab thickness is known, however, the slab modulus can be estimated. Conversely, if the slab modulus is known,or can be determined from simple tests such as

illustrated in Figure 4 for the rebound hammer, the slab thickness can be back-calculated.

(e) The method is general in nature, and is not based on a limited number of particular cases as are database approaches presented in References 11 and 12. This permits very useful and theoretically valid inferences to be made for a given pavement system by examining data collected from a wide variety of other dissimilar systems.

(f) Application of the procedure to actual field data from recent or on-going projects has confirmed that it yields very realistic, consistent and reliable results (7). Calculations performed follow a definite and closed loop, all but eliminating the probability of calculation errors.

(g) A number of interesting topics may be examined using this method. These include: the effect of number and spacing of sensors; correlation between backcalculated and intrinsic system properties, particularly with respect to the dynamic effect of the NDT procedure; examination of the effect of friction and bonding between layers, and comparison with results from an equivalent combined thickness approach; field determination of properties necessary in other aspects of pavement design, such as dowel concrete interaction, amount of load transferred by the critical dowel as well as by the entire dowel assembly, etc.

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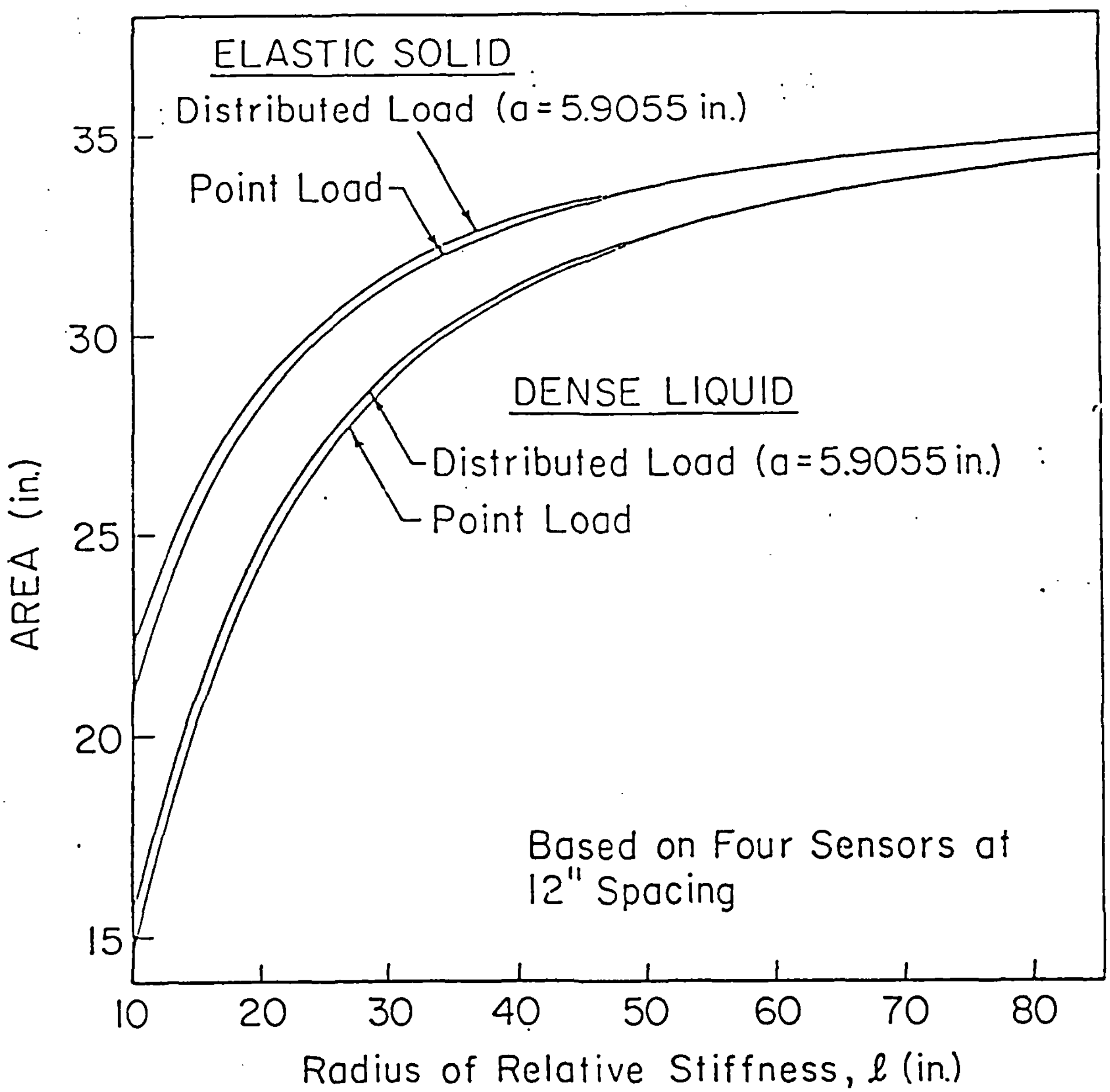

FIG. 1.- Variation of AREA with ℓ (Ref. 2)

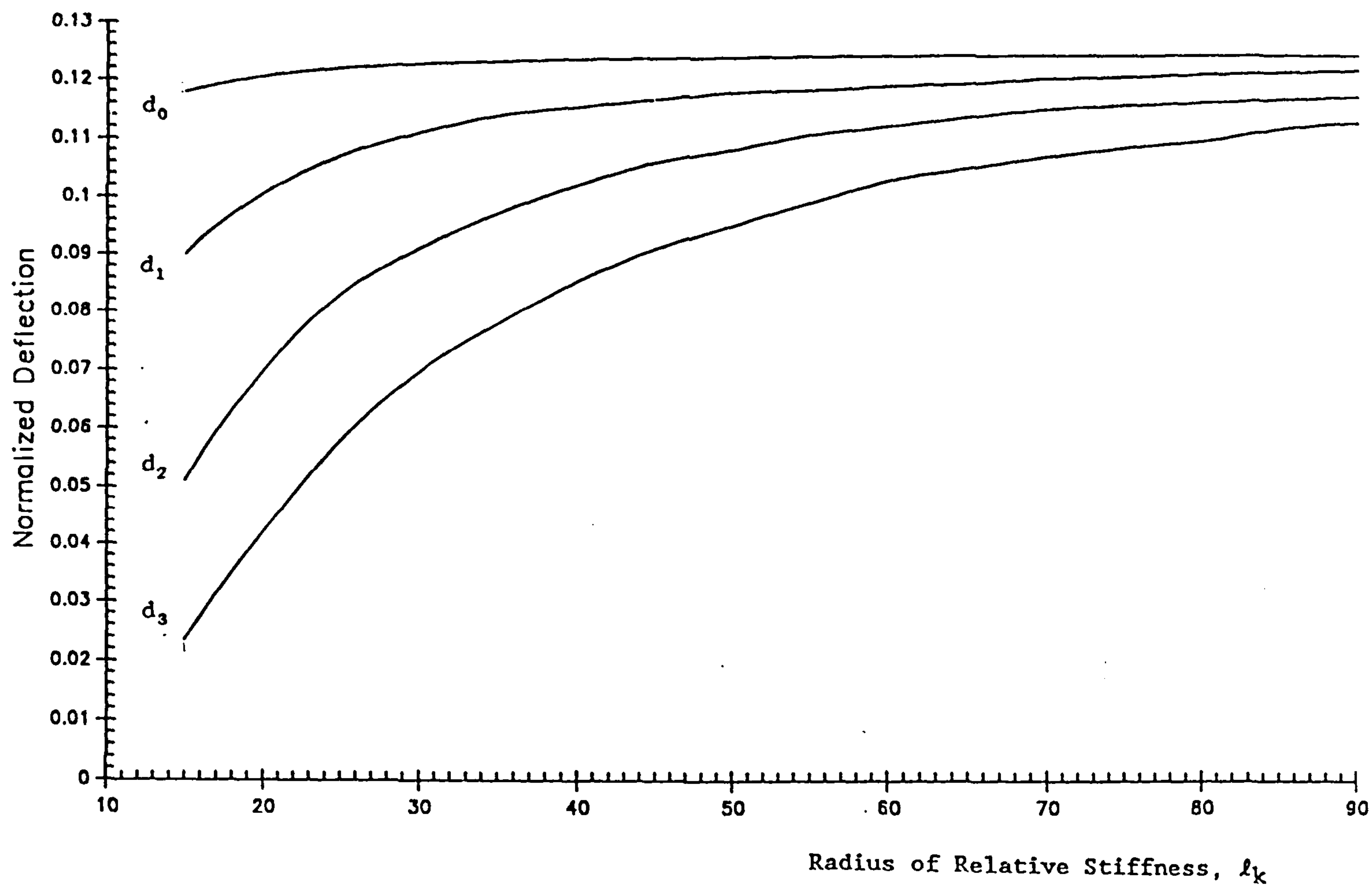

FIG. 2 · Variation of Dimensionless Deflections with ℓ:
(a) For Dense Liquid Foundation

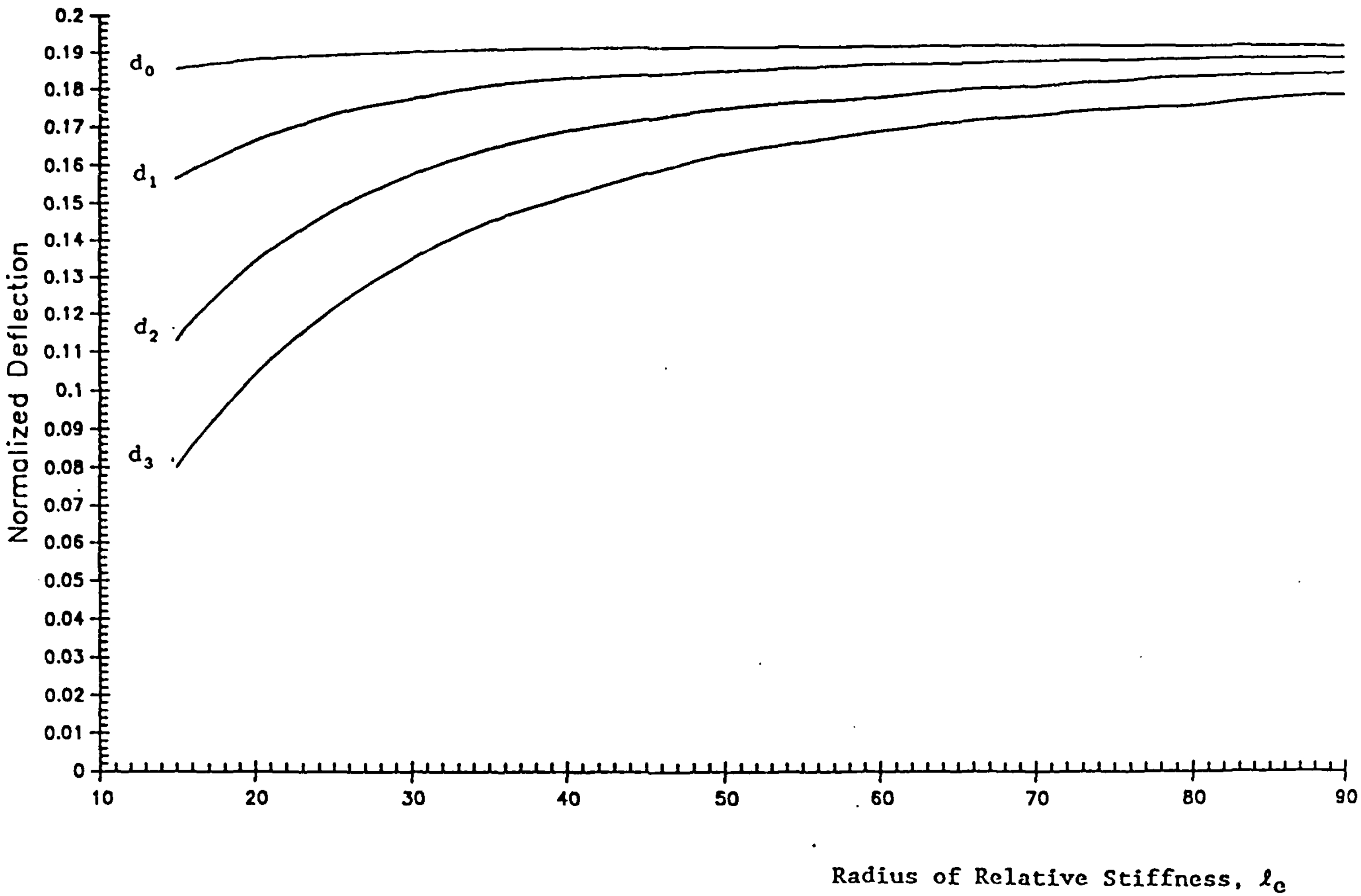

FIG. 3 - Variation of Dimensionless Deflections with ℓ:
(b) For Elastic Solid Foundation (Ref. 7)

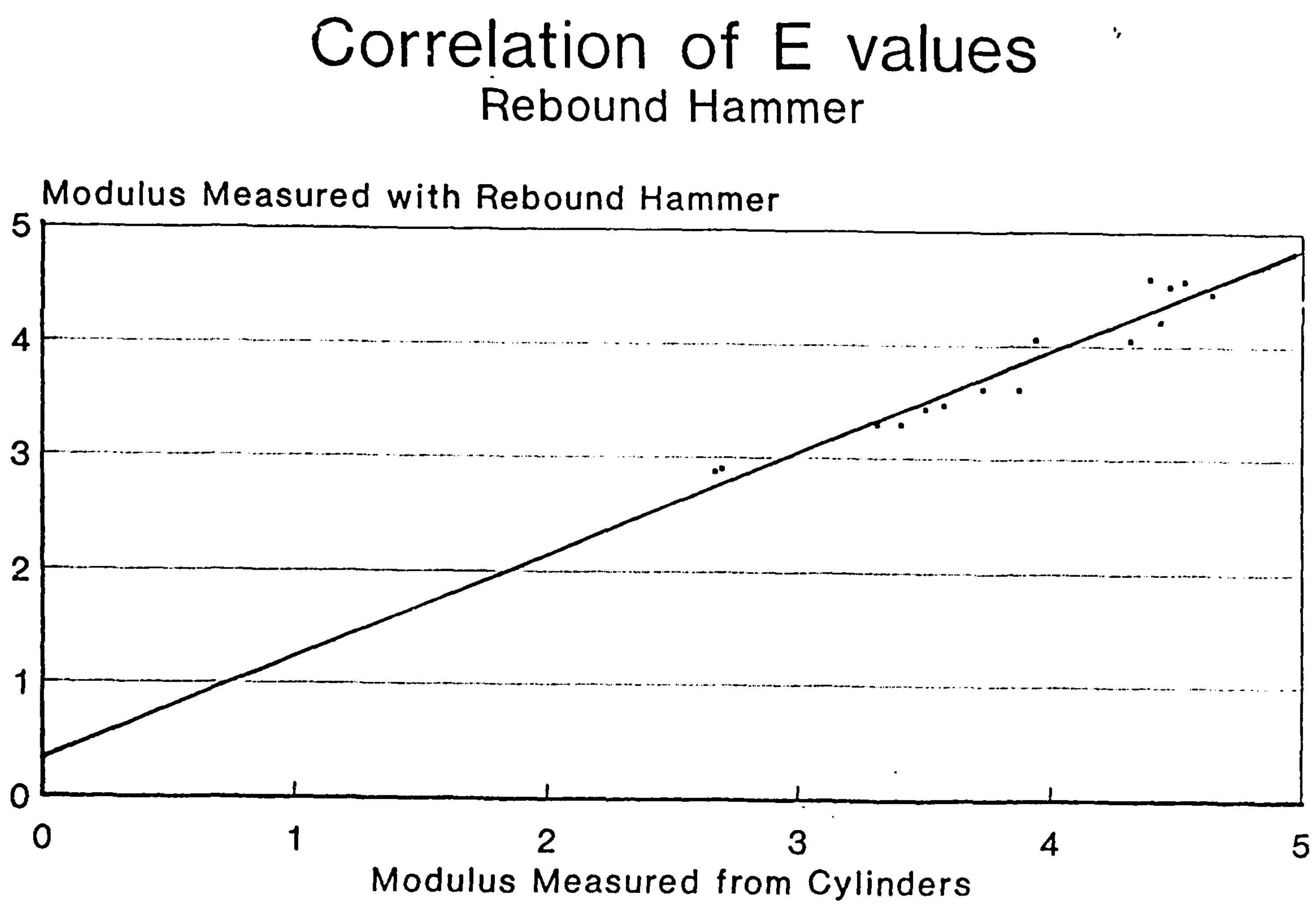

Fig. 4 - Correlation of Elastic Values for Concrete Measured from Compression Cylinders with Rebound Hammer Results

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